Eye movements and word skipping during reading: effects of word length and predictability

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Abstract

Eye movements were monitored as subjects read sentences containing high or low predictable target words. The extent to which target words were predictable from prior context was varied: half of the target words were predictable and the other half were unpredictable. In addition, the length of the target word varied: the target words were short (4-6 letters), medium (7-9 letters), or long (10-12 letters). Length and predictability both yielded strong effects on the probability of skipping the target words and on the amount of time readers fixated the target words (when they were not skipped). However, there was no interaction in any of the measures examined for either skipping or fixation time. The results demonstrate that word predictability (due to contextual constraint) and word length have strong and independent influences on word skipping and fixation durations. Furthermore, since the long words extended beyond the word identification span, the data indicate that skipping can occur on the basis of partial information in relation to word identity.

A great deal has been learned about the relationship between eye movements and cognitive processing during reading over the past thirty years (Liversedge & Findlay, 2000; Rayner, 1998, 2009a). One reason for this is that sophisticated models have been developed which yield specific and testable hypotheses about eye movement control in reading (see Rayner, 2009b). A second reason has been the development of gaze-contingent paradigms that give experimenters a great deal of control over the nature of the stimulus presentation (McConkie & Rayner, 1975; Rayner, 1975). Experiments using gaze-contingent paradigms have established that readers are able to pick up information from the word to the right of fixation. This *parafoveal preview benefit* results in shorter fixation times on a target word when the letters of the word were visible during the prior fixations as compared to when the letters were masked or replaced by other letters (Rayner, 1975). Besides resulting in shorter fixation times on a target word when subsequently fixated, parafoveal preprocessing also has an impact on the decision as to whether the next word will receive a fixation or it will be skipped. A word is skipped when it does not receive a direct fixation during first pass; skipping occurs quite frequently with 1/3 of all words, on average, being initially skipped during reading (Rayner, 1998).

Much research has been dedicated to the topic of word skipping during reading, and this has increased our understanding of the factors that determine when the eye guidance system generates a saccade to skip the next word. More specifically, three important facts have emerged regarding skipped words. First, word skipping is intimately related to word length: as the length of a given word increases, the probability that it will be skipped decreases (Brysbaert, Drieghe, & Vitu, 2005; Rayner & McConkie, 1976; Rayner, Sereno, & Raney, 1996). Thus, short words are much more likely to be skipped than long words: three letter words are skipped about 67% of the time, whereas 7-8 letter words are skipped only about 20% of the time (Rayner & McConkie, 1976)[1]. Second, when word length is matched, words that are predictable from prior text are more likely to be skipped than unpredictable words (Balota, Pollatsek, & Rayner, 1985; Drieghe, Rayner, & Pollatsek, 2005; Ehrlich & Rayner, 1981; Rayner & Well, 1996). Finally, high frequency words are also skipped more frequently than low frequency words when matched on length (Rayner et al., 1996), though the effect of frequency on skipping is not as large as either that of word length or predictability (for a discussion on effect sizes in word skipping studies, see Drieghe, Desmet & Brysbaert, 2007). But even though word length is the strongest predictor for skipping rates (Brysbaert, Drieghe & Vitu, 2005), the independent effects of predictability and frequency are numerically strong enough to rule out any account exclusively based on word length, as would be predicted by a random-walk model. It is also important to note that both word frequency (Inhoff & Rayner, 1986; Rayner & Duffy, 1986; Rayner et al., 1996) and word predictability (Ehrlich & Rayner, 1981; Rayner & Well, 1996; see Rayner, 2009a for further references on both effects) have strong influences on fixation times on words during reading: with word length matched, readers fixate for less time on high frequency words than on low frequency words and for less time on high predictable words than on low predictable words.

In the research reported here, we examined the relationship between word length and predictability and the effect of these variables on word skipping and fixation times on target words. While the facts mentioned above about skipping, word length, and word predictability are well established, the joint influence of word length and predictability on skipping and fixation times is still not fully understood. In the present research we addressed the issue of whether or not predictability influences the skipping of short, medium, and long target words equally, and the effect that predictability has on fixation times on words of different lengths when the target word is not skipped.

So far, the only study that directly examined the interplay between word length and predictability in the context of word skipping was reported by Drieghe, Brysbaert, Desmet and De Baecke (2004). They presented readers sentences in which a target word of either two or four letters was presented in a sentence that strongly increased the reader's expectation for a specific word. There were three types of target word: a predictable word, an unpredictable word that had the same word length as the predictable word, or an unpredictable word of different length. By combining the results for the two stimuli sets (i.e. with the predictable word being a 2 or a 4 letter word), they were able to examine the skipping rates of three words matched on word length: a predictable target word, an unpredictable target word presented in the same context, and an unpredictable target word which was presented in a different sentence frame that raised the expectation of a target word of a different word length. Their results showed that the predictable word was skipped more often than the unpredictable word of the same length. However, there was no difference in skipping rates between the two unpredictable target words even though one of these words had the same length as the predictable target word. These findings were interpreted as evidence for visual and linguistic factors independently affecting word skipping.

While the Drieghe et al. study was the first to examine the joint influence of predictability and word length on word skipping, there are several limitations to this study. To ensure high enough skipping rates to observe any potential effects of predictability and expected word length, Drieghe et al. used target words that were either two or four letters long. As a result, their observed skipping rates in the two letter-word conditions could be considered to have suffered from ceiling effects (predictable two-letter words were skipped on 79% of the trials). Equally important, their choice of word lengths limits the suitability of their experiment in relation to the examination of fixation times on the target words. There are two reasons for this. First, the very high skipping rates means that the proportion of trials on which the target word was fixated was seriously reduced, weakening the statistical power of the analyses of fixation durations. Second, very short words are more prone to receive "mislocated" fixations (Drieghe, Rayner, & Pollatsek, 2008; Nuthmann, Engbert, & Kliegl, 2005) - that is, fixations for which there is a discrepancy between where a saccade was targeted and where it actually landed. For very short words, this can often lead both to fixations unintentionally landing on a word, or to skipping of a word (for estimations of how often this would occur, see Engbert & Nuthmann, 2008; Nuthmann et al., 2005). In this way, fixation times on very short words do not necessarily produce very reliable effects, and we suspect that this was the case in the Drieghe et al. study, since their predictability manipulation had a profound effect on the skipping rates of their target words but missed statistical significance in some of the fixation time analyses.

Three other studies that used a slightly different methodology are relevant to this discussion of the effects of parafoveal word length information on the subsequent fixation times on those words during reading. By means of the gaze-contingent boundary paradigm, Inhoff, Radach, Eiter, and Juhasz (2003) manipulated the preview of the word length of a target word by removing a letter in a high or low frequency target word (e.g. *sub ect* as a preview for *subject*). When the eyes crossed the invisible boundary the incorrect preview was replaced by the target word. By comparing eye movement measures related to the processing of the parafoveal word as a function of correct word length preview, this experiment allowed Inhoff et al. to examine the *word length constraint hypothesis* which proposes that word length may be used to constraint the number of possible word candidates and as such, assumes linguistic function in the word recognition process. The idea that there could be cross-talk between low-level visual information (i.e. word length) and high-level language information was initially suggested by Hochberg

(1975) and is also present in Clark and O'Regan's (1999) ideas on parafoveal word recognition. If word length does constrain the number of lexical candidates, an interaction could be expected on the target word viewing times between the preview and the frequency manipulation in the sense that the correct word length information would be more helpful for the low-frequency target word. However, Inhoff et al. observed completely additive effects of these two factors and concluded – as did Drieghe et al. (2004) - that functionally distinct subsystems control the use of parafoveally visible spatial and linguistic information during reading.

However, some indications for the ability of word length to constrain potential lexical candidates have been observed. White, Rayner, and Liversedge (2005) examined the influence of parafoveal word length and contextual constraint on both fixation durations and word skipping. In a boundary change experiment they inserted a letter between a high or low predictable target word and the next word. Contrary to Inhoff et al., they observed an interaction between predictability and word length preview in that predictability influenced first-pass reading times on the target word when parafoveal word length was correct, but not when it was incorrect. This interaction was not significant for word skipping but a numeric trend pointed in the direction of the predictability effect being twice the size for skipping the correct previews versus the incorrect previews. A somewhat similar picture emerges in results reported by Juhasz, White, Liversedge, and Rayner (2008), who replicated White et al. (2005) and also observed a significant interaction between preview and predictability in fixation times on the target word (which was restricted to first fixation durations) but in that study there was no hint of such an interaction for the skipping rates of the target word. It is important to stress here that in contrast to the Drieghe et al. (2004) study where correct word length previews were presented, the incorrect word length preview manipulation does suffer from a few limitations. When planning the saccade towards the target word, the incorrect preview can cause the eyes to land on a non-optimal position within the word, a mechanism known to trigger re-fixations (McConkie, Kerr, Reddix, Zola & Jacobs, 1989; O'Regan, 1990) and as such, influence fixation times. In other words, questions can be raised as to whether effects observed in the fixation durations on the target word were caused by an incorrect restriction of potential word candidates on the basis of word length, or were a side-effect of landing on a non-optimal position within the target word after the display change had occurred. Likewise, one could object to comparing skipping of the target word in the White et al. and Juhasz et al. studies to word skipping in normal reading conditions because adding a letter between the target word and the next word creates a much longer preview. Readers typically land slightly left to center of a word (i.e. the *preferred landing location*, Rayner, 1979), so if the reader was aiming for this preferred landing position in the long word located in the preview, it would quite often be counted as a skip of the target word when the display changed back to the two separate words in these two experiments.

Taken together, Drieghe et al.'s findings and those of Inhoff et al. point in the direction of independent influences of word length and linguistic variables during parafoveal preprocessing, whereas the observations from White et al. (2005) and Juhasz et al. (2008) provide some evidence for the word constraint hypothesis, but exclusively in fixation durations and not in skipping rates. These studies indicate that the joint influence of word length and predictability on skipping and fixation times is not yet fully understood. Our main question in the present research was whether or not there would be an interaction between word length and word predictability in skipping and fixation times across a large range of word lengths with correct parafoveal previews. By using the full range of word lengths we can overcome the limitations associated with the Drieghe et al. (2004) study and by exclusively presenting correct word length previews we will be in a better position to interpret any observed effects compared to the studies using incorrect word length previews.

Examining fixation durations and word skipping simultaneously within the same experiment is important for another reason. Most experimental manipulations seem to affect both measures in a similar way, with increased processing difficulty of the parafoveal word typically being associated with both reduced skipping rates and with longer fixation durations when the readers do land on the word. In other words, fixation durations and skipping are often considered to be correlated measures of the same phenomenon: the amount of preceding parafoveal processing. However, experimental manipulations have been shown to differentially impact word skipping and fixation durations (see Drieghe, 2008 for a discussion). We mentioned above the White et al. (2005) and the Juhasz et al. (2008) studies which show a differential impact of word length previews on fixation times and skipping rates. Another discrepancy is observed for the finding reported by Henderson and Ferreira (1990) that increasing the foveal load by means of presenting a low-frequency versus a high-frequency foveal word leads to reduced parafoveal preview benefit. This effect has proven to be a robust finding in fixation times but two studies directly examining the impact of foveal load on subsequent word skipping were unable to obtain a significant interaction between foveal load and preview condition for skipping rates (Drieghe, Rayner, & Pollatsek, 2005; White, 2007). Rayner, Ashby, Pollatsek and Reichle (2004) also showed differential patterns for word skipping and fixation durations when examining the joint influence of frequency and predictability. Whereas a slightly larger predictability effect was observed for low frequency words compared to high frequency words in gaze duration (the sum of all fixations on a word prior to moving to another word), the skipping rates were such that only the high frequency predictable word was skipped reliably more often than the three other conditions in their orthogonal manipulation. These studies indicate the importance of examining the influence of factors on both fixation times and skipping rates, without assuming both measures will necessarily exhibit the same patterns.

If both word length and predictability are used jointly in relation to the decision of whether or not to skip a word, interactive effects should occur. For example, in a situation where context renders a particular word very predictable, and there is a parafoveal word length cue that is consistent with that word, then the likelihood of the word being skipped might be greater than would be the case if the decision to skip was made on the basis of either source of information alone. An alternative possibility is that there would be an effect of word length on word skipping independent of predictability. In such a situation, although both sources of information might inform the decision to skip, their influences would not jointly constrain lexical candidature and therefore skipping. With respect to fixation times, we anticipated longer fixation measures for longer words compared to shorter words (since longer words yield more refixations), and for unpredictable words compared to predictable ones. But there is again the question of whether or not there would be an interaction of length and predictability.

In addition to considering the joint influence of predictability and word length on word skipping, we also examined a phenomenon that has received little, if any, attention in the literature to date - namely, skipping of particularly long words (10 letters or longer). Indeed, even though eye movement studies examining fixation durations on long words are far from rare, especially in languages with flexible compounding rules such as German and Finnish, skipping of long words is usually not investigated due to extremely low skipping rates. In an extensive meta-analysis, Brysbaert et al. (2005) considered the data from all studies which examined skipping rates for words varying in word length, predictability, and frequency. Their metaanalyses showed that skipping of words longer than 8 letters was very rare, and those studies that did examine skipping rates were susceptible to floor effects in relation to manipulations of frequency and predictability. The reason for this is that it is extremely difficult to create sentences that feature long words that are high in frequency and/or predictable from the preceding context such that frequent skipping might occur. Word length and frequency are negatively correlated to a high extent with longer words tending to be of considerably lower frequency in English. Thus, in order to establish the efficacy of our predictability manipulation for the long words in the current research, a large scale norming study was also carried out (see below) in which we examined sentence fragment completion rates for our target words. The data collected in the sentence completion task provide an opportunity to determine whether our experimental stimuli at least offered the potential for predictability and word length to mutually constrain the candidate set in relation to the identity of the upcoming parafoveal target word. Given the relative lower frequency of longer words, it was important to establish the potential of our materials to make long target words very predictable based on preceding sentential context.

There is an additional theoretically important reason for examining skipping behavior for long words. Specifically, the extent to which a word that is skipped is processed during the prior fixation remains an issue of some debate (e.g. Radach & Kennedy, 2004; Rayner & Juhasz, 2004; Reichle, Rayner, & Pollatsek, 2003), and views on this matter differ considerably. According to the E-Z Reader model (Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle et al., 2003), a word is skipped because it is recognized (or more precisely recognition is imminent) in parafoveal vision. This view is different from other models such as the EOVP model (Brysbaert & Vitu, 1998) that states that word skipping is based on more coarse information and consists of an educated guess, mostly determined by parafoveal word length, and that skipping the word will not hinder text understanding. Other models such as SWIFT (Engbert, Nuthmann, Richter, & Kliegl, 2005) for instance, also assume that skipping occurs based on incomplete parafoveal word recognition. When skipping of very long words (10 letters or longer) is concerned, limitations in visual acuity will restrict the amount of parafoveal preprocessing that can be carried out (particularly in relation to the final letters of those long words). It is therefore theoretically interesting to investigate the oculomotor decisions the processing system makes given the impossibility of acquiring complete letter information for those last letters. This is particularly the case in relation to the positions various models hold regarding the level of parafoveal preprocessing required in relation to a decision to skip the following word. Results of studies using the moving window technique have been consistent in showing that the perceptual span in alphabetical languages such as English extends from 3-4 letters to the left of fixation and 14-15 letters to the right of fixation (McConkie & Rayner, 1975; Miellet, O'Donnell, & Sereno, 2009; Rayner, 1975; Rayner, Castelhano, & Yang, 2009). Throughout this area, word length information can be obtained. However, the word identification span, which encompasses the area in which visual acuity is great enough to allow for the extraction of letter identification (and therefore, successful word identification), does not exceed 7-8 letter spaces to the right of fixation (Rayner, 1998, 2009a). As a consequence, the long target words in the current study partially fell outside this area and the decision to skip them would have to be made on the basis of only partial information about word identity. Thus, the current research is also important in that extending findings from previous studies to a larger range of word lengths allowed us to establish whether word skipping decisions are made more on the basis of predictability information when information about letter identity is limited for the longer target words. If this is the case, then it is likely an interaction between word length and predictability should occur with stronger predictability effects for the longer words.

A final controversial issue that the current study speaks to is whether or not skipping a word leads to a longer fixation duration immediately prior to the skip. This question also has importance for models of eye movement control in reading. Both SWIFT (Engbert, et al., 2005) and Glenmore (Reilly & Radach, 2006) assume that lexical processing occurs in parallel over the perceptual span while E-Z Reader (Reichle, et al., 1998; Reichle, et al., 2003) assumes that lexical processing is serial. Due to this latter assumption, E-Z Reader predicts that fixation durations on a word prior to a skip should be longer than those prior to a fixation on the subsequent word. In contrast, SWIFT and Glenmore do not necessarily predict such a difference (although the current version of SWIFT can accommodate it for certain types of words). The inflated fixation effect predicted by E-Z Reader is due to the need to cancel a planned saccade to the next word in order for it to be skipped (other than in cases where skipping occurs due to oculomotor error). In relation to this question, the data are somewhat mixed as some studies (Rayner et al., 2004; Drieghe et al., 2005; Pollatsek, Rayner, & Balota, 1986; Pynte, Kennedy, & Ducrot, 2004; Rayner, Juhasz, Ashby, & Clifton, 2003) have found inflated fixations prior to skipping, while others (Drieghe et al., 2004; Engbert, Longtin, & Kliegl, 2002; Radach & Heller, 2000) have not (and see Kliegl & Engbert, 2005 for a case in which inflated fixation durations were found prior to skipping long or low frequency words, but not short or high frequency words). The data on this issue are noisy mostly because experimenters cannot precisely control when readers skip a word (for a discussion: see Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007). Given the theoretical importance of the fixation durations prior to skipping or landing on words, these fixation durations were also analyzed[2].

In summary, our goal in the present research was to examine the joint influence of word length and predictability on word skipping and fixation durations. The range of word lengths was more comprehensive than in any other previous study and we included the theoretically interesting category of long words that extend beyond the word identification span.

Norming Study

The purpose of analyzing the cloze data from the sentence completion norming study was to firmly establish the potential of our materials to induce strong expectations for specific upcoming words of a particular length (short, medium or long). In the predictable condition, pairs of sentences were prepared wherein certain target words (varying in length) were designed to be highly predictable given the preceding context. This was done via manipulating the first sentence in the pair (see Table 1). While the first sentence of each pair of sentences varied to make the target word predictable or unpredictable, the second sentence was identical across the item pairs.

Method

Subjects. Ninety-three undergraduate students (all native speakers of English) from the University of California, San Diego participated in the norming study. None of these subjects participated in the eye tracking experiment.

Materials. Each stimulus item consisted of two sentences. Target words were embedded into the second sentence which was identical in both predictability conditions. The first sentence varied to manipulate predictability (see Examples 1 and 2 in Table 1 and Appendix). Target words were short (4-6 letters), medium (7-9 letters), or long (10-12 letters). In total there were 54 experimental items, 18 from each word length condition, matched for frequency (see Table 1), F

< 1, according to the HAL log frequency count (Burgess, 1998, Burgess & Livesay, 1998). In choosing target words of different lengths, we utilized the HAL log frequencies for the words in the complete database of the English Lexicon Project (Balota et al. 2007). A word with a HAL log value of 8.3 or less would occur 10 or less times per million words (low frequency words) and a word with a HAL log value of 9.9 or more would occur 50 or more times per million words (high frequency words). The mean frequency for our short, medium, and long words (see Table 1) was at the 89th, 96th, and 98th percentiles respectively, indicating that our targets were relatively high frequency words.

As an additional check regarding frequency, we obtained the lemma frequencies for each of our target words using the Corpus of Contemporary American-English (Davies, 2008) to determine the relevant words for each target's lemma and then summed the HAL frequencies of these words (the mean of the logs of these summed HAL frequencies are also shown in Table 1). These lemma frequencies indicated that the short and medium words were not significantly different, $t < 1$. However, the lemma frequency for the long words was lower than for the short words, $t(34) = 2.05$, $SE = .66$, $p = .048$, and marginally lower than the medium words, $t(34) = 1.88$, $SE = .62$, $p = .069$[3].

Insert Table 1 about here

Procedure. Subjects were given the two sentences up to but not including the target word and asked to fill in what word they thought would come next. Sentences were presented on a computer monitor and subjects typed their completion response.

Results and Discussion

The results of these responses showed a strong effect of the predictability manipulation ($F(1,51) = 716.3$, $p < .001$), with target word completions being produced significantly more often in predictable than unpredictable contexts. There was no main effect of length, indicating that correct target word completions were equally likely in each of the length conditions, and no interaction between the two factors, all $Fs < 1$ (see Table 1). Recall, however, that we could not orthogonally manipulate predictability and target word length for our eye-tracking experiment (i.e., a short, medium, or long word did not appear in the same predictable or unpredictable sentence frame). Instead, the experimental situation was one in which the target word, and therefore, the parafoveal target word length cue, remained constant whilst contextual predictability was manipulated. Note also that while the identity of the predictable target word was likely, based on the preceding context, it was not completely predictable. Furthermore, since target word length was manipulated across conditions, the size of the candidate set in relation to the target word identity should change systematically with word length. That is, there would be potentially more, readily accessible, short words that could appear in the position of the target (regardless of how predictable they were) than long words because there are more high frequency short than long words in English. It is for this reason that the cloze data provide an opportunity to determine whether our experimental stimuli offered the potential for predictability and word length to mutually constrain the likelihood of the identity of the parafoveal target word (i.e. interactive effects).

To make this concrete, consider a pair of hypothetical examples in which a subject reads an experimental sentence in which context provides two likely “candidates” for the upcoming word, one with a cloze probability of 60% and the other with a cloze probability of 40%. In the first of these examples the word with the higher cloze is long and the word with the lower cloze is short. If the lexical processing system (that is centrally involved in decisions of where and when to move the eyes) uses word length and predictability information jointly, then knowledge that the upcoming word is long would enable the system to further constrain the "candidate" set thereby further increasing the likelihood of skipping the target word. Now consider the second example where both of the candidate words are short. In this second example no further constraining of the candidate set in terms of word length is possible. The alternative theoretical possibility is that the probability of the upcoming word being skipped or very briefly fixated will be additively influenced by the predictability and length cues, but will not attain increased likelihood due to the joint influence of both.

To better understand how predictability and word length cues might constrain target word identity in the eye movement experiment (see below) we further analyzed the cloze data by examining the length of the words that subjects produced as completions to the predictable and unpredictable sentence frames. In this way we could assess whether the "candidate" words for our stimuli would offer the opportunity to obtain an interaction in the eye movement experiment. We did two sets of item analyses. In one, we included both cloze completions that were the target word, as well as cloze completions that were not the target word. In the other set of analyses, we only included completions that were not the target word. The completion data are shown in Table 2.

Insert Table 2 about here

There are several striking aspects of the data. First, unsurprisingly, the mean length of the word that subjects produced in the cloze task in the predictable conditions increased from 5.3 characters in the short condition to 9.5 characters in the long condition when we included correct completions. This increase is largely due to the fact that subjects were very likely to produce the predictable word, and the length of the predictable word differed systematically under the different conditions. In contrast, the completion data in the unpredictable conditions showed no increase in the mean length of the words produced across conditions (varying between 5.6 and 6.9 characters, but with no significant trend). Together, these data indicate that given a strong predictability cue to an upcoming long word, subjects are far less likely to spontaneously produce an alternative long word, than they are to produce an alternative short word. This in turn indicates that word length is, potentially, a far stronger constraint on the identity of an upcoming parafoveal word when that word is long compared to when it is short.

To formalize these claims, we also computed the probability that subjects produced a completion word that was in the same length category as the target word, given either a predictable or an unpredictable context (see Table 2). Unsurprisingly, there was a main effect of predictability, $F(1,51) = 196.64$, $MSE = .021$, $\eta_p^2 = .79$, $p < .001$, with completions being far more likely to be the same length as the target under predictable than unpredictable conditions. There was also a main effect of length, $F(2,51) = 22.27$, $MSE = .031$, $\eta_p^2 = .47$, $p < .001$, with completions being longer on average for sentences in which the intended target word was longer than shorter. This effect is largely due to the effects of the predictability cues in half the experimental conditions. Critically, however, there was a reliable interaction, $F(2,51) = 17.05$, $MSE = .021$, $\eta_p^2 = .40$, $p < .001$. The difference between the predictability conditions, for the probability that subjects would produce a completion word that was in the same length category as the target, was greater for the long target word condition than for the short word condition, $F(1,34) = 37.64$, $MSE = .019$, $\eta_p^2 = .53$, $p < .001$, or the medium word length condition, $F(1,34) = 37.64$, $MSE = .022$, $\eta_p^2 = .23$, $p < .005$. Additionally, this difference was greater for the medium length words than for the short words, $F(1,34) = 6.17$, $MSE = .021$, $\eta_p^2 = .15$, $p < .05$. Thus, it was the case that in the cloze task, the predictability cue provided by the sentential context very strongly influenced the likelihood that subjects produced a completion word of a particular length. These data, therefore, constitute a compelling demonstration that the stimuli employed in the eye movement experiment were appropriate to allow us to, potentially, observe interactive effects of word length and predictability in word skipping and reading times.

We also carried out an analysis to investigate the probability that subjects produced a completion word that was in the same length category as the target word, when completions that were the target word were excluded. These analyses showed a main effect of target length, $F(2,51) = 31.91$, $p < .001$. The probability that incorrect completions were short, medium or long words was .61, .42, and .15, respectively. This effect confirms that subjects were more likely to complete the fragments with short than long words. In fact, of the total incorrect fragment completions (i.e., regardless of the word length of the correct completion), 31% were short words, 19% were medium and only 4% were long words.

Eye Movement Experiment

Method

Subjects. Twenty-eight undergraduate students (all native speakers of English) from the University of California, San Diego participated in the experiment. They all had either normal uncorrected vision or corrected vision (via contact lenses or glasses). They were all naïve concerning the purpose of the experiment.

Apparatus. Eye-movements were recorded via an SR Research Ltd. Eyelink 2000 eye-tracker. This eye-tracker samples and records the position of the reader's eye every ½ millisecond, and has high spatial resolution of 0.01° (with an average of about .3° during the experiment). The EyeLink 2000 system uses an Ethernet link between the eye tracker and display computers, which supplies real-time gaze position data. Subjects were seated 55 cm away from a 19 inch ViewSonic VX922 LCD monitor. The text was presented in a fixed width 14 point Consolas font as black letters on a white background. At this viewing distance, 3.2 letters equaled 1° of visual angle. Although viewing was binocular, eye movements were only recorded from the right eye.

Materials. The materials were the same as used in the norming study.

Procedure. At the start of the experiment, subjects completed a calibration procedure by looking at a sequence of three fixation points randomly presented horizontally across the middle of the computer screen. A validation procedure then repeated this process and returned the average error between calibration and validation. If this error was greater than .4 degrees of visual angle the entire procedure was repeated. At the start of each trial, a black square (50 pixels wide and 50 pixels tall) appeared on the left side of the computer screen which coincided with the left side of the first letter in the sentence. Once a stable fixation was detected within this area the sentence replaced it on the screen. All sentences were presented vertically centered on the computer monitor and sentence order was randomized for each subject. Both sentences were presented simultaneously on the same screen. Subjects were instructed to read silently for comprehension and to press a button on a key pad when they finished reading the sentence. Comprehension questions appeared on the screen after a third of all the items. These 'yes/no' questions required the subjects to understand the meaning of the sentence and respond via a button press.

Results

Comprehension rates were high (87%). Trials in which there was a blink, or track loss on the target word or during an immediately adjacent fixation were removed prior to analysis (3.8% of trials). Return sweeps from the first to the second sentence that landed on or beyond the target word were also excluded from analysis (4.0% of trials). Fixations shorter than 80 ms, which were within 1 character of a previous or subsequent fixation, were combined with that fixation, all other fixations less than 80 ms were eliminated (1.9% of fixations). Additionally, data points more than 2.5 standard deviations above the mean within a condition were replaced by the value of 2.5 standard deviations above the mean, truncating less than 2% of the remaining data. Data loss affected all conditions similarly.

Six standard eye movement measures (Rayner, 1998) were examined (see Table 3): *first fixation duration* (the duration of the first first-pass fixation on the target word), *single fixation duration* (cases in which the reader made only one first-pass fixation on the target word), g*aze duration* (the sum of all first-pass fixations on the target word before moving to another word), *total reading time* (the sum of all fixations on the target word including regressions), *skipping probability* (the probability that the target word was skipped on first pass reading), and the *number of fixations* (the number of fixations the target word received during first pass reading not counting instances of skipping). In addition, a less standard measure (*adjusted gaze duration*) was also computed in which the gaze duration was adjusted to account for skipping. Specifically, if the target word was skipped, it was assigned a value of zero in this measure (Just & Carpenter, 1980). Data were subjected to 3 (word length: short, medium, long) X 2 (predictability: high versus low) ANOVAs using subjects (*F1*) and items (*F2*) as random factors; counterbalance list was also included as a between subject/item variable (Pollatsek & Well, 1995). Follow-up contrasts of the length effect are reported with F statistics as well so that the variability due to counterbalance list could be taken into account consistent with the overall ANOVA.

Insert Table 3 about here

Fixation times. As seen in Table 3, the length of the target word had little effect on first fixation duration, $F1(2,52) = 2.37$, $MSE = 424.15$, $\eta_p^2 = .08$, $p > .10$; $F2 < 1$, or single fixation duration, $F1(2,52) = 3.71$, $MSE = 572.85$, $\eta_p^2 = .13$, $p < .05$; $F2 < 1$. However, word length did have an influence on gaze duration, though the effect was only marginally significant by subjects $F1(2,52) = 3.04$, $MSE = 1478.77$, $\eta_p^2 = .11$, $p = .056$; $F2\ (2,48) = 3.23$, $MSE = 1395.08$, $\eta_p^2 = .12$, $p < .05$. Follow-up contrasts indicate that gaze durations on short and medium length words did not differ, $F1 < 1$; $F2\ (1,32) = 1.37$, $MSE = 1281.87$, $\eta_p^2 = .04$, $p > .10$. The gaze difference between medium and long words approached significance only in the subjects analysis, $F1(1,26) = 3.04$, $MSE = 1335.46$, $\eta_p^2 = .11$, $p = .09$; $F2\ (1,32) = 1.77$, $MSE = 1582.63$, $\eta_p^2 = .05$, $p > .10$. However, the gaze difference between short and long words was significant, $F1(1,26) = 4.85$, $MSE = 1770.97$, $\eta_p^2 = .16$, $p < .05$; $F2\ (1,32) = 6.80$, $MSE = 1320.81$, $\eta_p^2 = .18$, $p < .05$. Word length also influenced total reading time (which includes rereading), $F1(2,52) = 7.01$, $MSE = 199.95$, $\eta_p^2 = .21$, $p < .01$; $F2\ (2,48) = 5.13$, $MSE = 2213.20$, $\eta_p^2 = .18$, $p < .05$. Again, follow-up contrasts indicate that total reading time did not differ between short and medium length words, $F1(1,26) = 1.76$, $MSE = 1915.65$, $\eta_p^2 = .06$, $p > .10$; $F2\ (1,32) = 1.94$, $MSE = 2164.54$, $\eta_p^2 = .06$, $p > .10$. However, total reading time to long words was greater than to medium length words though this effect was only marginal in the items analysis, $F1(1,26) = 5.92$, $MSE = 1931.32$, $\eta_p^2 = .19$, $p < .05$; $F2\ (1,32) = 3.05$, $MSE = 2394.78$, $\eta_p^2 = .09$, $p = .09$, and between long and short words, $F1(1,26) = 12.65$, $MSE = 2152.89$, $\eta_p^2 = .33$, $p < .005$; $F2\ (1,32) = 10.85$, $MSE = 2080.27$, $\eta_p^2 = .25$, $p < .005$. Despite the lack of statistical significance for some of these pairwise comparisons there was a significant linear trend of length with increasing fixation times to longer words for both gaze duration, $F(1,26) = 4.85$, $MSE = 1770.97$, $\eta_p^2 = .16$, $p < .05$, and total time $F(1,26) = 12.65$, $MSE = 2152.89$, $\eta_p^2 = .33$, $p < .01$, with no quadratic trend, Fs < 1[4].

Predictability had a significant effect on all fixation duration measures wherein readers looked at low predictable words longer than high predictable words. For first fixation duration the effect size was 11ms, $F1(1,26) = 9.89$, $MSE = 499.17$, $\eta_p^2 = .28$, $p < .005$; $F2\ (1,48) = 11.29$, $MSE = 255.89$, $\eta_p^2 = .19$, $p < .005$; for single fixation duration it was 13ms, $F1(1,26) = 10.46$, $MSE = 584.78$, $\eta_p^2 = .29$, $p < .005$; $F2\ (1,48) = 12.32$, $MSE = 310.79$, $\eta_p^2 = .20$, $p < .005$; for gaze duration it was 18ms, $F1(1,26) = 15.45$, $MSE = 861.83$, $\eta_p^2 = .37$, $p < .005$; $F2\ (1,48) = 17.36$, $MSE = 494.90$, $\eta_p^2 = .27$, $p < .001$; and for total reading time it was 33ms, $F1(1,26) = 19.50$, $MSE = 2308.82$, $\eta_p^2 = .43$, $p < .001$; $F2\ (1,48) = 43.36$, $MSE = 736.16$, $\eta_p^2 = .48$, $p < .001$;. The length by predictability interaction never approached significance, F's near or below 1, p's > .15.

Word Skipping. Not surprisingly, skipping probability was influenced both by word predictability, [$F1(1,26) = 8.53$, $MSE = 2.1$, $\eta_p^2 = .25$, $p < .01$; $F2\ (1,48) = 8.74$, $MSE = 1.3$, $\eta_p^2 = .15$, $p < .01$] and word length, [$F1(2,52) = 16.00$, $MSE = 2.8$, $\eta_p^2 = .38$, $p < .001$; $F2\ (2,48) = 12.73$, $MSE = 2.5$, $\eta_p^2 = .35$, $p < .001$], (see Table 3)[5]. Short words were skipped more than medium length words, [$F1(1,26) = 12.74$, $MSE = 3.0$, $\eta_p^2 = .33$, $p < .005$; $F2\ (1,32) = 9.01$, $MSE = 3.1$, $\eta_p^2 = .22$, $p < .005$], or long words, [$F1(1,26) = 23.11$, $MSE = 3.7$, $\eta_p^2 = .47$, $p < .001$; $F2\ (1,32) = 18.92$, $MSE = 3.2$, $\eta_p^2 = .37$, $p < .001$]. Additionally, medium length words were skipped more than long words, [$F1(1,26) = 5.80$, $MSE = 1.6$, $\eta_p^2 = .18$, $p < .05$; $F2\ (1,32) = 5.50$, $MSE = 1.2$, $\eta_p^2 = .15$, $p < .05$]. However, there was no hint of an interaction between predictability and word length (*F*s < 1)[6].

Number of fixations. Word length exerted an influence on the number of fixations the target word received [$F1(2,52) = 9.98$, $MSE = .026$, $\eta_p^2 = .28$, $p < .001$; $F2\ (2,48) = 12.73$, $MSE = 2.5$, $\eta_p^2 = .35$, $p < .001$]. Follow-up contrasts indicated that short words received fewer fixations than medium length words, [$F1(1,26) = 7.65$, $MSE = .020$, $\eta_p^2 = .23$, $p < .01$; $F2$ $(1,32) = 12.62$, $MSE = .010$, $\eta_p^2 = .28$, $p < .005$], or long words, [$F1(1,26) = 16.47$, $MSE = .032$, $\eta_p^2 = .39$, $p < .001$; $F2$ $(1,32) = 24.28$, $MSE = .014$, $\eta_p^2 = .43$, $p < .001$]. However, the difference between medium and long words was only marginally significant, [$F1(1,26) = 4.06$, $MSE = .027$, $\eta_p^2 = .14$, $p = .054$; $F2$ $(1,32) = 3.30$, $MSE = .017$, $\eta_p^2 = .09$, $p = .079$] with longer words receiving more fixations. There was no significant effect of predictability ($F1 < 1$; $F2$ $(1,48) = 1.81$, $MSE = .010$, $\eta_p^2 = .04$, $p > .10$) and no interaction between word length and predictability (all *F*'s < 1) although this could be due to floor effects because re-fixations were quite rare overall.

Adjusted Gaze Duration. While the standard measures reported above are informative, it is the case that they overestimate the amount of time literally associated with how long readers look at target words as a function of length and predictability. Specifically, the standard fixation time measures are all contingent on there being a fixation on the target word, and skipping is computed separately. Thus, we computed an alternative gaze duration measure in which a processing time value of zero was assigned to skipped words. Via this analysis (see Table 3), there were strong effects of length, [$F1(2,52) = 17.66$, $MSE = 2264.69$, $\eta_p^2 = .41$, $p < .001$; $F2$ $(2,48) = 10.25$, $MSE = 2853.59$, $\eta_p^2 = .30$, $p < .001$]. Follow up contrasts indicate that adjusted gaze duration was shorter for short than for medium length words, [$F1(1,26) = 15.90$, $MSE = 1710.94$, $\eta_p^2 = .38$, $p < .001$; $F2$ $(1,32) = 6.34$, $MSE = 2978.56$, $\eta_p^2 = .17$, $p < .05$], or long words, [$F1(1,26) = 16.47$, $MSE = .032$, $\eta_p^2 = .39$, $p < .001$; $F2$ $(1,32) = 17.85$, $MSE = 3257.70$, $\eta_p^2 = .36$, $p < .001$], and marginally shorter for medium length words than for long words, [$F1(1,26) = 4.06$, $MSE = .027$, $\eta_p^2 = .14$, $p = .054$; $F2$ $(1,32) = 4.63$, $MSE = 2324.52$, $\eta_p^2 = .13$, $p < .05$]. There were also strong effects of predictability, [$F1(1,26) = 29.18$, $MSE = 1211.88$, η_p^2

$= .53$, $p < .001$; $F2\ (1,48) = 25.58$, $MSE = 884.15$, $\eta_p^2 = .35$, $p < .001$]. But again, the interaction did not approach significance (Fs < 1).

Launch sites. The average launch site of the saccade that either landed on or skipped the target word (see Table 3) did not differ across the predictability conditions, Fs < 1. However, launch sites were closer to the start of short words (5.48 character spaces) than to medium (6.13 characters) and long words (6.18 characters): short vs. medium [$F1(1,26) = 4.45$, $MSE = 2.91$, $\eta_p^2 = .15$, $p < .05$; $F2\ (1,32) = 6.34$, $MSE = 2978.56$, $\eta_p^2 = .17$, $p < .05$], short vs. long, [$F1(1,26) = 6.78$, $MSE = 2.07$, $\eta_p^2 = .21$, $p < .05$; $F2\ (1,32) = 17.85$, $MSE = 3257.70$, $\eta_p^2 = .36$, $p < .001$], medium vs. long, ts <1. As with all the previous measures, length did not interact with predictability, Fs < 1. Given that targets are more likely to be skipped when the previous fixation (launch site) is close to the target word (Rayner et al., 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995) an analysis of launch site was conducted including skipping as a factor, thus comparing launch sites for skipped targets to those for fixated targets. However, in a standard ANOVA this analysis would have very little statistical power due to the relatively low rate of skipping (especially for the long words). Therefore, the analysis was performed using a linear mixed model (LMM) specifying subjects and items as crossed random effects using the lme4 package in R (2007). An advantage of such an analysis is that it results in substantially less loss of statistical power in unbalanced designs than traditional ANOVAs over subjects and items (see Baayen, 2008; Baayen, Davidson, & Bates, 2008). As can be seen from Table 3, launch sites were closer to the target word when it was skipped than when it was fixated, b = -2.84, SE = .43, p < .001. Additionally, the LMM analysis found a small effect of predictability with words in the unpredictable condition having closer launch sites than in the predictable condition, b = -.44, SE

= .22, $p < .05$. This small effect may be the result of the very different initial sentences for the predictable and unpredictable conditions. No other effects were significant[7].

Insert Table 4 about here

Fixation Durations Prior to Skips. When the duration of the fixation prior to skipping a target word was compared to fixation durations when the reader did not skip the target word (see Table 4), using LMM (with the same factors as used in the analysis of launch sites) there was a significant effect of skipping only for the medium length words, $b = 21.96$, $S.E. = 10.32$, $p < .05$, with no other effects approaching significance. It is important to stress here that due to our focus on long words, our design is less suited for looking at these fixation durations. For instance, the means for fixation durations prior to skipping our longest words are based on no more than 2.2 and 3.4 observations on average per subject for the unpredictable and predictable conditions respectively.

Discussion

The main finding from the present experiment is that word predictability had a strong effect on both skipping of and fixation time on target words independent of the length of the target word. While word length also influenced both skipping and fixation times, there was no significant interaction across the different measures we examined. Even the adjusted gaze duration (a measure that is sensitive to both fixation time and whether or not a word was skipped) yielded no interaction of the two variables. Although the size of the predictability effect was slightly larger for long words (36 ms in adjusted gaze) than short (29 ms) and medium (25 ms) length words, the interaction did not approach significance. Note that this was the case, even though our analyses of the cloze data demonstrated that our stimuli clearly had the potential to produce interactive effects of length and predictability. Thus, our results suggest that parafoveal word length cues, and the predictability of a particular word based on prior sentential context, both exert strong, but independent influences on lexical candidates that are likely to correspond to an upcoming word that has not yet been fixated. Furthermore, given the centrality of lexical identification procedures to the oculomotor decisions of where and when to move the eyes during reading, our findings strongly suggest that predictability and word length independently constrain eye movement control.

It is also interesting to note that while the launch sites were closer to the target word when it was skipped, this effect did not interact with target word length. That is, when the target word was skipped readers' fixations were no closer to it in the medium and long conditions than in the short condition. Therefore, the skipping of long words in the current experiment, while less frequent than the other length conditions, is not the result of trials with abnormally close launch sites. These findings nicely tie in with results reported by Drieghe et al. (2004), who also observed independent effects of visual and linguistic factors on word skipping for very short words (2 and 4 letters long) and with the findings of Inhoff et al. (2003), who observed independent effects of linguistic variables and parafoveal word length cues on fixation times on a target word.

The current study is the first to demonstrate skipping rates for long words (10 letters or longer) that are sufficiently high to allow for a meaningful examination of the impact of predictability on word skipping (see Brysbaert, et al., 2005). As stated in the Introduction, this group of words are theoretically interesting; because the long words extended beyond the limits of the word identification span, the decision to skip the upcoming long word must have been based on partial word information (i.e., on more coarse visual information than is typically available and used to make similar saccadic targeting decisions for shorter words). Various models uphold different views on the amount of processing of the parafoveal word that has to occur in order for the system to decide to skip the next word. One of these is the EOVP model (Brysbaert & Vitu, 1998) in which word skipping is mostly based on word length and consists of an educated guess in that the system has learned from prior experience that it can usually skip words of a certain length without hindering overall text comprehension. This educated guess seems highly compatible with the observation that the system will skip a long word even though full identification of the final letters has not occurred due to visual acuity limitations. However, a study that established the advanced level of processing associated with the skipping of predictable words of average word length, casting doubts on the educated guess based on coarse information being the default procedure for word skipping, was reported by Drieghe et al. (2005). They examined skipping rates for predictable versus unpredictable words (mean word length: 4.7 characters) but also included a condition using a nonword parafoveal preview that was identical to the predictable target word except that a single letter was changed towards the end of the word (e.g. *livor* as a preview for *liver*). This rather subtle manipulation nullified the effect of predictability resulting in skipping rates for the visually similar non-word that were comparable to those for non-words that were visually dissimilar from the predictable word. This is indicative of the predictable parafoveal word being processed to an advanced level prior to the oculomotor control system making the decision to skip it. However, it is interesting to note that while the predictability effect disappeared in the Drieghe et al. study when only a single letter was changed in the preview of the predictable word, a very similar manipulation in a study by Balota et al. (1985) had no effect (i.e. *cahc* was skipped as often as *cake*), indicating incomplete identification of previews. This difference may be due to the poorer viewing conditions that subjects experienced in the Balota et al. experiment as the twenty years in between these two studies were accompanied by considerable advances in video monitor technology and as a consequence legibility. Reduced clarity associated with the stimuli could have prevented the advanced level of processing in the Balota et al. study (1985) observed by Drieghe et al. (2005). Based on the current data and those of Drieghe et al., it appears that an advanced level of lexical access is attained prior to the oculomotor control system making the decision to skip the next word, as is evident from a sensitivity to conflicting orthographic evidence such as a competitor word of the same length as that anticipated, or even a single letter mismatch in a parafoveal preview of an anticipated word. Note that this sensitivity maintains even when context is highly predictive of an upcoming word that shares many of the characteristics of the candidate in the parafovea, and in particular its length. Note, however, that the system can also make a decision to skip a word when that word is long and the identification of its final constituent letters is incomplete, either due to the target word stretching too far into the parafovea in the case of a long word as in the current study, or when confronted with sub-optimal viewing conditions as in the Balota et al. study.

Whereas the current experiment provides one of the strongest indications to date that the oculomotor control system can make the decision to skip a word based on partial parafoveal orthographic information, it is important to note that the architects of the E-Z Reader model anticipated such a possibility. As Pollatsek, Reichle, and Rayner (2006) stated: "the higher-level linguistic processing that is going on in parallel with word identification is sometimes sufficient to "fill in" the gaps in the sentence meaning that is being constructed" (p.12). What are the implications of the current data for the architecture of the E-Z Reader model? In E-Z Reader, word skipping is based on the following sequence of events. The programming of an eye movement starts when the word processing system reaches a stage from which word identification of the currently fixated word becomes likely. This stage is called the familiarity check (L1). At this stage, a word is not yet fully recognized, but the dynamics in the lexicon are such that it is likely to become so within a limited time period. When the familiarity check for the currently fixated word *n* has occurred, the eye guidance system starts to program a saccade to the next word *n + 1.* Visual attention and the eyes remain on word *n* until it is completely processed (lexical access). Upon full identification of word *n* (L2), attention shifts to word *n + 1* and the eyes are expected to follow as soon as the eye movement programming is completed. If, however, the familiarity check of word *n + 1* is completed and if the programming of the initial eye movement has not yet reached its final ballistic stage, then the eye movement program towards word *n + 1* can be cancelled and replaced by a new program to word *n + 2*. In this situation, skipping of word *n + 1* will take place. The crucial point is that the decision to skip word *n + 1* is not triggered by full lexical identification of word *n + 1* but by the successful familiarity check. As such, it is actually an oversimplification to infer that E-Z Reader assumes a word is skipped because it has been fully recognized.

Another model that states that a word can be skipped based on incomplete identification is SWIFT (Engbert et al., 2005), in which multiple words in the perceptual span are processed simultaneously. According to SWIFT, saccades are targeted to the word with the highest amount of lexical processing. If word *n+1* has passed the peak of lexical processing (and this usually happens in the model before full lexical identification has occurred) and is surpassed in terms of the amount of lexical processing of word *n+2*, the saccade will be targeted towards *n+2* and *n+1* will be skipped. Whereas this idea seems compatible with the observation that long words can be skipped based on incomplete identification, it would require an actual simulation within SWIFT to see whether the model can account for the patterns observed in the current experiment. In SWIFT, there is a strong relationship between lexical processing rate and the distance from a word to the current fixation position, whereby lexical processing is seriously reduced as the word is located further away from the current fixation location. As such, it seems unlikely that an incompletely identified long word *n+1* would be surpassed in terms of lexical activity by word *n+2*, which would be located quite far into the parafovea (or even in the periphery). But again, a simulation within the SWIFT model is necessary to assess the compatibility of the current data set with the model's assumptions.

Further research is required to establish under which circumstances the system will commit to making a decision to skip an upcoming word, particularly in relation to partial parafoveal information, and also, particularly for words that are easy to process because they are predictable. The fact that the long words used in the current study were indeed easy to process is apparent from the fixation durations observed on them, which were shorter than fixations on similar words reported in other studies (Rayner et al., 1996). Note, however, that these fixation durations are comparable to those obtained in experiments using similar equipment and student groups (Kliegl, Grabner, Rolfs & Engbert, 2004).

It should also be noted that whereas Rayner et al. reported effects of word length on first fixation duration and single fixation duration, we did not observe such effects in the present study. The source of the difference between the present findings and those of Rayner et al. (1996) isn't fully apparent. However, what is important to note is that across both studies (as well as Vitu, O'Regan, & Mittau, 1990) there was an effect of word length on gaze duration; gaze durations were longer on long words than on short words. Obviously, this makes sense in that as word length increases, the probability of refixating a word increases (Rayner &

McConkie, 1976; Rayner et al., 1996) and much of the variability in gaze durations is due to readers making more than one fixation on a word. Skipping rates were also higher in the present study than what is typically reported (Rayner, 1998). In all likelihood, this is due to our (successful) attempts to ensure high enough skipping rates to avoid floor effects in any of the conditions by selecting from the highest frequency words in each word length condition and having sentence completion ratio's for the unpredictable words that were well above zero.

Finally, the duration of fixations prior to word skipping is a point of special importance for models of eye movements during reading. In particular the E-Z Reader model predicts that the fixation durations prior to an intended word skip should be inflated relative to cases where the word was fixated due to the need to cancel a planned saccade. With respect to this controversial issue of inflated fixation durations prior to skips, the results of our analyses, like much of the prior research, are somewhat mixed and should be treated with care, given the limited amount of data for skipping of the long words. Specifically, we found evidence for inflated fixations prior to skips, but only for the medium length words (7-9 letters long). It is unclear why there were no effects for the longer words; obviously, there are less data (due to less skipping), but there was not much indication of an effect. It is possible that mislocated fixations (Nuthmann, et al., 2005; Rayner, Warren, Juhasz, & Liversedge, 2004; Drieghe, et al., 2008) are a factor. As already mentioned, E-Z Reader only predicts increased fixation durations prior to an intended skip. However, mislocated fixations can occur due to oculomotor errors. Oculomotor errors are the result of variability (both random and systematic) in saccade landing positions around saccade targets (McConkie, Kerr, Reddix, & Zola, 1988). The systematic error component of the oculomotor system is such that short saccades tend to overshoot targets while long saccades tend to undershoot them. Therefore, the fixated cases in the long word condition are likely to include some intended skips and the skipped cases in the short word condition are likely to include some intended fixations. The medium length words are less likely to suffer from these mislocated fixation artifacts.

Overall, the data that we obtained are relevant to current models of eye movement control in reading, such as E-Z Reader, SWIFT, and Glenmore. Clearly, word length and predictability are two of the primary influences on fixation durations and word skipping, and their combined influence on such behavior has obvious implications for the mechanistic processes that govern decisions about when and where to move the eyes. The extent to which different models centralize lexical processing in relation to oculomotor decisions is important here. The present data constrain the nature of the lexical identification process, and this relates directly to shorter or longer fixations and increased or reduced skipping probabilities. Given the direct relationship between lexical processing and saccadic commitments in E-Z Reader, the mapping between the present data and processing in the model is clear. One of the contributions of the current experiment is to demonstrate that there is no need to build into the E-Z Reader model a restriction of word candidates during the lexical processing of the parafoveal word based on the parafoveal word length.

In summary, the current experiment examined the influence of predictability on the fixation durations and skipping rates of words varying in length. Results suggest that word length and predictability independently affect word skipping and fixation durations. Moreover, skipping of long words that extend beyond the word identification span suggests that on occasions the system responsible for saccadic control will commit to skipping a word even when a parafoveal word's identity can only be assumed based on partial parafoveal orthographic information.

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Footnotes

1. Interestingly, whereas word length has a pronounced and consistent influence on reading times (i.e. longer words are associated with longer gaze durations and reduced skipping rates), word length effects in visual word recognition have been either non-existent or associated with longer reaction times, with recent evidence pointing towards decreased RT's for words of 3-5 letters, null for words of 5-8 letters and increased RT's for words of 8-13 letters (New, Ferrand, Pallier, & Brysbaert, 2006).

2. Note, however, due to our focus on words longer than typically used in skipping experiments, it is unlikely that our analysis will hold sufficient power to allow us to determine unequivocally whether inflated fixation durations occur prior to skipping. This is because even when long words are easy to process, they are usually not skipped very often (see Brysbaert et al, 2005).

3. Lemma frequencies are correlated to an even higher extent with word length than word frequency (i.e. short words have on average a higher frequency than long words) making it difficult to obtain perfect matching on both measures. More importantly, word frequency explains more variance in, for instance, lexical decision times than lemma frequency does (Brysbaert & New, 2009). Consequently, we consider word frequency to be the critical measure for matching.

4. Note that these trend analyses only apply to the subject means as the length factor was a between-item factor in the items analyses.

5. Normally, skipping rate is determined as the percent of trials in which the target is not fixated during first pass reading. However, the pattern of effects and their statistical significance

remained unchanged when skipping rate was calculated as the percent of trials in which the target was never fixated during first pass or subsequent reading (total skip rate in Table 3).

6. When readers did not skip the target word, there was a strong effect of word length on landing position in the word, with means of 2.5, 3.1, and 3.8 characters into the word for the short, medium, and long words, respectively [$F1(2,52) = 29.44$, $p < .001$; $F2(2,48) = 30.02$, $p < .001$]. However, there was no influence of predictability on landing position [$F1(1,26) = 1.49$, $p > .20$; $F2(1,48) = 2.78$, $p > .10$] and no significant interaction between word length and predictability [$F1(2,52) = 1.48$, $p > .05$; $F2(2,48) = 3.12$, $p > .05$).

7. Since the length by predictability interaction was not significant in other measures, the LMM analysis did not include this term or the length by predictability by skipping interaction term in an attempt to gain power for the remaining terms. However, in an LMM analysis that included these terms neither approached significance.

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Table 1. Example stimuli in the experiment, as well as word frequency and cloze probabilities for the different word length conditions.

1. Gary had become a compulsive liar.

   He just couldn't seem to tell the *truth* about anything. (Predictable target)
2. Gary has some mental health issues.

   He just couldn't seem to tell the *truth* about anything. (Unpredictable target)

Word Length	Word frequency mean log HAL	Mean number of characters	Unpredictable cloze probability	Predictable cloze probability
Short	9.18 (9.66)	5.16	.14	.70
Medium	9.04 (9.62)	7.67	.17	.77
Long	8.84 (9.00)	10.39	.13	.75

note: mean lemma frequencies appear in parenthesis after the word frequencies. HAL is based on approximately 400,000,000 words.

Table 2. Analyses of the Cloze Data. P = Predictable, U = Unpredictable

Measure	Short Sentence Fragments		Medium Sentence Fragments		Long Sentence Fragments	
	P	U	P	U	P	U
Length of completion word (target word completions included)	5.3	5.5	7.3	6.4	9.5	6.9
Length of completion word (target word completions excluded)	6.0	5.6	6.4	6.3	6.9	6.4
Probability of a completion of the same length category as target	.89	.69	.88	.51	.81	.22

Table 3. Target word measures of processing time (first fixation duration, single fixation duration, gaze duration, total time, number of fixations and adjusted gaze duration), skipping rate, total skip rate (see Footnote 5), and launch site.

Measure	Short		Medium		Long	
	P	U	P	U	P	U
First Fixation	205 (6.3)	209 (6.4)	193 (5.6)	204 (4.0)	195 (4.6)	211 (5.5)
Single Fixation	206 (6.4)	212 (7.1)	191 (6.0)	203 (4.9)	192 (5.8)	210 (6.0)
Gaze Duration	211 (7.4)	222 (9.0)	213 (9.1)	231 (8.0)	222 (10.5)	246 (10.1)
Total Time	227 (9.7)	247 (10.6)	227 (9.6)	268 (12.0)	250 (11.5)	287 (13.2)
Number of Fixations	1.04 (.02)	1.07 (.03)	1.11 (.03)	1.15 (.04)	1.20 (.05)	1.19 (.05)
Adj. Gaze	136 (8.9)	162 (11.4)	168 (10.7)	193 (11.4)	184 (13.1)	221 (11.6)
Skipping Rate	36 (3.5)	28 (3.5)	22 (3.3)	18 (2.7)	18 (3.3)	10 (2.3)
Total Skip Rate	33 (3.2)	21 (3.1)	20 (3.3)	15 (2.3)	17 (3.0)	8 (1.9)
Launch Site	5.48	5.47	6.35	5.91	6.16	6.19

Note: Processing times are in milliseconds; rates in percentages; launch site is in character spaces before the start of the target word, standard errors appear in parenthesis. P = Predictable, U = Unpredictable.

Table 4. Fixation measures for processing time (fixation prior to skip, fixation after skip) and launch sites.

Measure	Short		Medium		Long	
	P	U	P	U	P	U
Fix Prior to Skip	206	220	221	234	204	206
Fix Prior to Fix	211	212	203	204	207	208
Launch Prior to Skip	3.68	3.71	3.40	3.42	3.69	3.71
Launch Prior to Fix	6.52	6.08	7.04	6.60	6.80	6.36

Note: All cell means are derived from the beta values of the LMM analyses. Times are in milliseconds. Launch sites are in characters from the beginning of the target region where a launch site of 1 indicates that the saccade was launched from the last character of the previous region. P = Predictable, U = Unpredictable.

APPENDIX: Stimuli used in the study. The first sentence in each triplet was the predictable condition initial sentence and the second was the unpredictable condition initial sentence. Each stimulus consisted of one of these two variants along with the third sentence of the triplets, which contained the target word (in bold italics). The log HAL frequency appears in brackets following the target sentence.

Short length target condition
Frank had way too many beers at the nightclub. (predictable)
Frank enjoyed frequently going to nightclubs. (unpredictable)
He was so ***drunk*** last night that he had to go home early and sleep.[8.89]

Jack had been married for many years now.
Jack works very hard and is almost always happy.
He loves his ***wife*** Joanne, and isn't afraid to show her affection.[10.56]

Gary had become a compulsive liar.
Gary had some mental health issues.
He just couldn't' seem to tell the ***truth*** about anything.[10.87]

Henry left the store without paying for the book.
Henry began reading a new science fiction book.
He was ashamed to admit he ***stole*** the book.[8.22]

Carl went to visit a redwood forest.
Carl went on a trip last Tuesday.
Carl saw a ***tree*** that looked as tall as a skyscraper.[10.21]

Thomas is afraid of clowns.
Thomas is easily spooked.
His friends took him to a ***circus,*** where he nearly fainted from fright.[8.13]

Luke was surprised to hear a very loud mooing sound from his backyard.
Luke spent a lot of money fixing the broken fence in his backyard.
It turns out a couple of ***cows*** broke through the fence.[8.22]

John went home for Thanksgiving dinner.
John went home to visit his family.
His mom cooked the best ***turkey*** and John ate a big portion.[9.53]

Larry didn't want Lucy to find him.
Larry was angry with Lucy.
He was ***hiding*** behind the garage where Lucy couldn't see him.[8.82]

Ruby was recklessly speeding on the highway.
Ruby was driving on a long, empty highway.
It wasn't long before the ***police*** pulled her over and gave her a ticket for speeding.[10.78]

Henry felt like going for a swim.
Henry recently moved into a new house.
He stepped into the ***pool*** in his backyard.[9.69]

Liz's mom planned a wonderful surprise for her daughter's birthday.
Liz's mom was very creative and wanted to do something special for her daughter.
She made a ***cake*** that was three feet high and decorated it with flowers.[8.74]

Hank is scared of eight legged bugs.
Hank has always been a fearful person.
He screamed when he saw the ***spider*** on the window.[8.85]

Henry felt sick and didn't want to go to school today.
Henry caught a bit of a cold over the weekend.
When his teacher noticed he was ***absent*** she marked it on the attendance sheet.[8.01]

Bill carried an umbrella with him to work today.
Bill wasn't looking forward to working outside.
He knew it'd ***rain*** today because he checked the weather forecast.[9.79]

Harry doesn't want to hurt his head if he falls off his bike.
Harry occasionally rides his bike to school in the morning.
He was nervous when he lost his ***helmet*** so he asked his mom to buy him a new one.[8.66]

Sarah could feel her tears rolling down her cheeks.
Sarah had always been a very self-conscious person.
She didn't want John to see that she was ***crying*** so she turned away and wiped her eyes.[8.84]

Paul hadn't eaten a single thing in days.
Paul went out with his friends last night.
He was so ***hungry*** that he ate everyone else's leftovers at dinner.[8.75]

Medium length target condition
Britney always drives way too recklessly.
Britney is in a really bad mood today.
She just got into an ***accident*** that wrecked her car.[9.32]

Beth loves performing in front of the camera.
Beth is my best friend's youngest daughter.
She wants to be an ***actress*** when she grows up.[8.52]

Isaac's plane arrived just a few hours ago.
Isaac just got back from a long trip overseas.
Jessica went to the ***airport*** to pick him up.[9.38]

Timothy went to the optometrist and found out he was near-sighted.
My friend Timothy enrolled in the same class with me this quarter.
He brings his ***glasses*** to class with him to see the blackboard.[9.05]

After the honeymoon, Mary felt sick to her stomach and didn't have her period.
Mary just got married and went on her honeymoon with her husband Joe.
She thinks she is ***pregnant*** so she bought a test to find out.[9.25]

Chelsea got on the freeway during rush hour.
Chelsea was late to her Biology lecture.
She tried to avoid the ***traffic*** but that turned out to be impossible.[10.14]

The secretary's wrist was sore from all the typing she did at her computer.
The secretary's computer has been doing strange things this past week.
She really wanted to get a new ***keyboard*** to see if that would help the problem.[10.47]

Lenny and Lisa got married last Saturday.
I really like hanging out with Lenny and Lisa.
I went to their ***wedding***, which everyone agreed was beautiful, and a lot of fun.[9.44]

Harold made sure his girlfriend wouldn't know about the birthday party.
Harold was sending his girlfriend balloons and a dozen red roses.
He wanted to ***surprise*** her so he told all their friends to keep it a secret.[9.78]

Sharon recently passed away in a car accident.
Sharon was in a bad car accident recently.
Last weekend I went to her ***funeral*** with all her friends and family.[8.08]

Norman is now a senior citizen and doesn't have to work anymore.
Norman has always hated the harsh winters of New England.
Now that he is ***retired***, he moved down to a nice condo in Florida.[8.68]

Eunice went to the zoo and saw a huge animal with a trunk for a nose.
Eunice went to the wildlife zoo to see all the different animals.
She really liked watching the ***elephants*** eating peanuts.[7.19]

Jeff didn't want to take the stairs to his office on the tenth floor.
Jeff drove downtown to his new job at the office building.
He had to wait a while for the ***elevator*** in order to avoid walking up the stairs.[8.08]

Mark would always howl whenever there was a full moon.
Even Mark's friends thought he was a complete lunatic.
He was convinced that he was a ***werewolf*** and no one could change his mind.[8.06]

My sister snuck downstairs to the Christmas tree.
My younger sister Margaret is very materialistic.
She always counted her ***presents*** before our parents woke up.[9.16]

A family recently moved into the house next to Tammy's.
Tammy is an excellent cook and loves making treats.
She decided to take a big batch of brownies to her ***neighbors*** and welcome them to the block.[8.74]

Phil took out his ruler and laid it on the table.
Phil wanted to buy a cover for his new table.
He needed to ***measure*** the table to find out how big of a tablecloth to get.[9.89]

Nancy bought some new brushes and a canvass from the art supply store.
Nancy really loved her family and liked doing special things for them.
She was about to start a new ***painting*** of her mother and father.[8.61]

Long length target condition
Megan decided one day to stop eating meat.
Megan went to go grab lunch with some co-workers.
She officially declared herself a ***vegetarian*** at lunch today.[8.38]

Oscar met someone who spoke with a heavy accent.
Oscar met someone new at the bus stop today.
Oscar could not ***understand*** a word he was saying.[11.59]

Yvonne noticed the sun was shining extra bright today.
Yvonne finished her math homework and went outside.
She put on a pair of ***sunglasses*** to reduce the glare from the sun.[8.14]

Ross's entire house started to shake violently.
Ross usually panics during emergency situations.
Luckily he'd been through an ***earthquake*** before so he knew that he should get underneath a desk.[8.63]

Dwayne dribbled the ball up the court and scored with a slam-dunk.
Dwayne played a lot of sports when he was in elementary school.
Dwayne had been very good at ***basketball*** even when he was young.[9.19]

Helen and Jacob started dating one year ago today.
Helen loves spending time with her boyfriend Jacob.
For their ***anniversary***, they went to an expensive restaurant.[8.73]

Catherine wanted to bake a tasty dessert.
Catherine was eager to help her mother out.
She gathered all of the ***ingredients*** for the cookies that were listed on the recipe.[8.74]

Tommy needed to write a report about pigmies but had no idea what they were.
Tommy wrote fiction books and tried to keep them as realistic as possible.
He used an ***encyclopedia*** to gather the information he needed.[8.44]

Some babies look into mirrors and think that there's another baby there.
Babies tend to have difficulty differentiating between appearances and reality.
They don't know that it's only a ***reflection*** of themselves in the mirror.[8.41]

Larry never thought that Jim would ever get married.
Larry hadn't heard from his friend Jim in over ten years.
Then just last week, he received an ***invitation*** to his wedding.[8.28]

Jimmy didn't know the meaning of the unfamiliar word.
Jimmy was having a lot of trouble with his homework.
Without a ***dictionary***, he never would have figured it out.[9.51]

Our fourth grade teacher quit her job halfway through the school year.
Mrs. Perkins was pregnant and went into labor a month before her due date.
They had to bring in a ***substitute*** to take over her class.[9.03]

Linda was very hungry and wanted to get food.
Linda and Raul are close friends from college.
Raul decided to take Linda to a ***restaurant*** downtown that served Italian food.[9.04]

Henry needed an instrument that could help him with his math homework.
Henry's supervisor sent him out to buy some supplies during lunchtime.
He bought a ***calculator*** at the office store.[8.26]

The foreign ambassador needed someone to help him talk to people in America.
The ambassador from Spain decided to visit America on a goodwill mission.
He hired a ***translator*** to accompany him during his stay.[8.02]

It was very cold outside and Jim felt like it was freezing.
Jim put his keys in his picket and grabbed his jacket.
He decided to check what the ***temperature*** was outside today.[9.57]

Tad and his sister were always reading at home.
Tad and his sister grew up in a poor neighborhood.
Their parents didn't own a ***television*** so library books really helped them pass the time.[10.02]

Marco really wanted a tasty snack and a glass of milk.
Marco came home late after everyone had gone to bed.
He opened the ***refrigerator*** and took out the leftovers from the night before.[7.52]